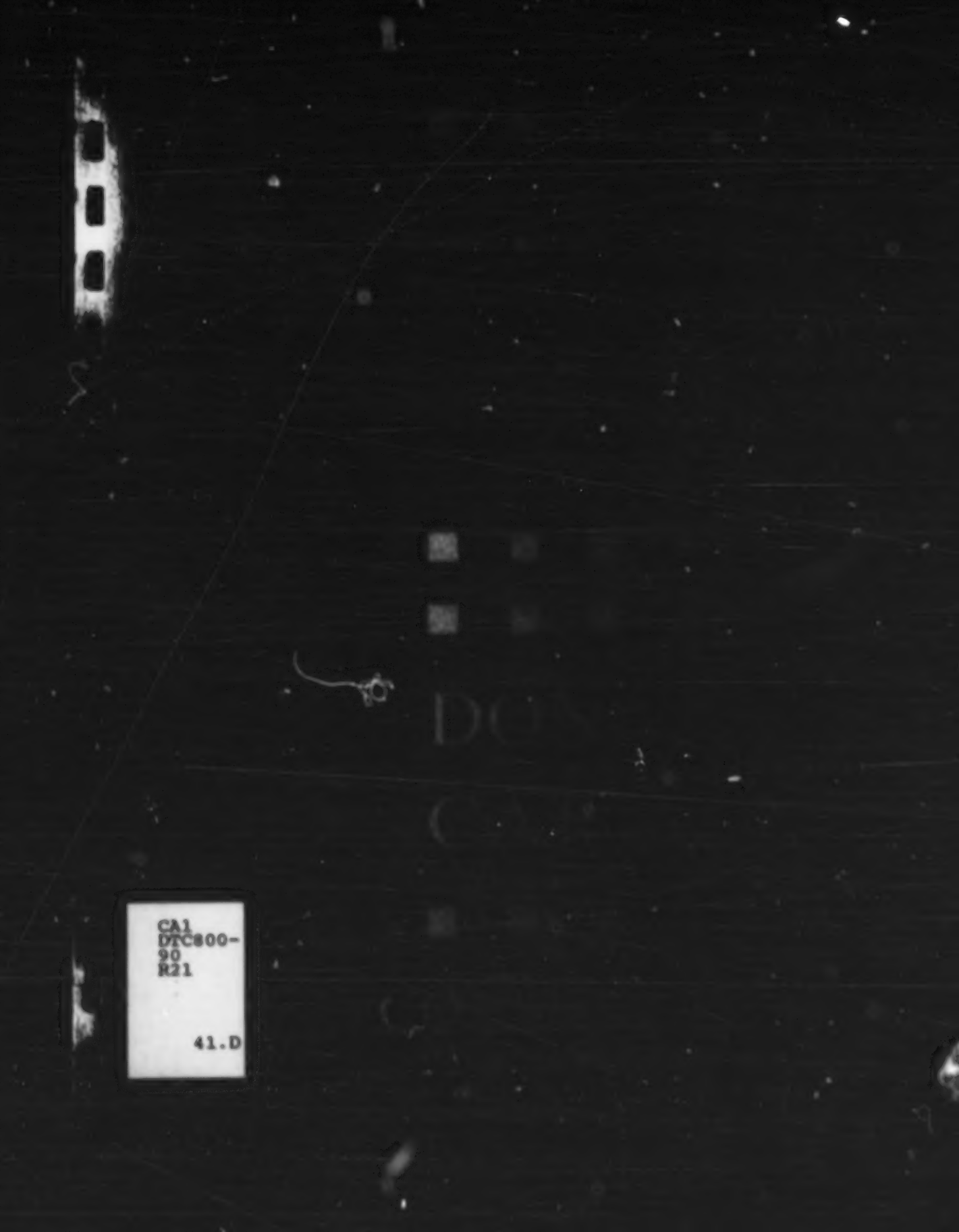
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RESULTS OF COMPARATIVE MODEL TESTS WITH A CONCEPTUAL HULL FORM AND THE ORIGINAL R-CLASS ICEBREAKER

prepared for
TRANSPORTATION DEVELOPMENT CENTRE
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TRANSPORT CANADA
November 1990

prepared by
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Un sommaire en français de ce rapport est inclus avant la table des matières.

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16. Abstract

A series of model tests were conducted to ascertain the ice and open water performance of a conceptual bow form as compared to the Original R-Class icebreaker.

Experiments in the towing tank were broken down into two parts: calm water resistance and seakeeping experiments. Experiments in the ice tank were also broken down into two parts: level ice resistance and presawn ice resistance.

Test results have shown that a more efficient icebreaking bow may be achieved without unduly degrading the ice clearing ability, open water resistance, and seakeeping performance.

Although the decrease in level ice resistance is impressive, it is not considered to be optimum and an additional testing program is strongly recommended.

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16. Résumé

Une série d'essais, en modèle réduit, a été effectuée pour évaluer les comportements dans la glace et en eau libre d'un nouveau concept de proue en comparaison d'un brise-glace de classe R.

Les essais dans le bassin des carènes furent de deux types: résistance en eau libre et tenue en mer. Les essais dans le bassin à glaces se scindèrent en résistance dans la glace uniforme et dans la glace morcelée.

Les résultats des essais mettent en évidence une nette amélioration de la capacité de briser la glace sans pour autant affecter sa facilité à déplacer les glaçons, sa résistance en eau libre et sa bonne tenue en mer.

Malgé une impressionnante diminution de la résistance à l'avancement dans la glace, on croit qu'il est encore possible d'apporter des améliorations et il est fortement recommandé de poursuivre les essais.

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SUMMARY

This report documents the results of a model test program devised to compare the efficiency of a new concept of ice-breaking bow to the performance of the Original R-Class.

Similar seakeeping and ice resistance tests were conducted on two 1:20 models in both the Ice Tank and the Towing Tank at the Institute for Marine Dynamics in St. John's.

Test results have indicated that:

1. the new bow concept, which was termed Carter Bow Form, has a lower effective power in calm water than the Original R-Class;
2. both designs have similar seakeeping performance;
3. the Carter Bow Form has a lower level ice resistance than the Original R-Class;
4. the clearing ability of both designs is virtually the same.

Although the decrease in level ice resistance is impressive, taking into account that the Original R-Class is particularly efficient, this is not considered to be optimum and additional tests are strongly recommended.

SOMMAIRE

Le présent rapport fait état d'essais, en modèle réduit, pour comparer l'efficacité d'un nouveau concept de proue brise-glace par rapport aux performances du navire de classe R.

Des essais similaires ont été effectués sur deux maquettes à l'échelle 1:20 dans le bassin à glaces et le bassin des carènes de l'Institut de dynamique marine à St-Jean.

Les résultats des essais nous amènent à conclure que:

1. le nouveau concept de proue, qu'on a baptisé proue Carter, a une résistance moindre à l'avancement dans les eaux calmes;
2. les deux formes ont des tenues en mer équivalentes;
3. la proue Carter a une résistance moindre dans la glace et peut progresser plus facilement;
4. les deux proues peuvent déplacer les glaçons avec une égale facilité.

Malgré l'impressionnante réduction de résistance dans les glaces, on croit qu'il est encore possible d'apporter des améliorations et on recommande fortement de continuer les essais sur la proue Carter.

TABLE OF CONTENTS

	Page
1. INTRODUCTION	1
2. DESCRIPTION OF MODELS	2
3. TEST PROGRAM	3
4. OPEN WATER TESTS	5
4.1 Calm Water Resistance Experiments	5
4.2 Seakeeping Experiments	5
5. ICE TESTS	9
6. ANALYSIS AND DISCUSSIONS OF RESULTS	14
6.1 Original R-Class	14
6.2 Carter Hull Form	16
7. CONCLUSIONS	19
8. REFERENCES	21

APPENDIX A Abbreviated Lines Plan

APPENDIX B Original R-Class - Math Model Input and Output Data

APPENDIX C Carter Hull Form - Math Model Input and Output Data

6 VHS Videos ans Numerous Slides and Photographs Accompany this Report

LIST OF FIGURES

		Page
Figure 4.1	Predictions of Effective Power Versus Ship Speed	6
Figure 5.1	Regressions Equations for Level Ice Resistance	13
Figure 6.1	Comparison of Measured Ice Resistance with Other Predictors and Predictions by Carter's Math Model ORIGINAL R-CLASS	15
Figure 6.2	Comparison Between Ice Resistance Measurements and Predictions by Carter's Math Model CARTER HULL FORM	18

LIST OF TABLES

		Page
Table 2.1	Hydrostatic Particulars	2
Table 3.1	Initial Test Program For Both Models	4
Table 3.2	Additional Test Program For Carter Hull Form Model	4
Table 4.1	Results of Calm Water Resistance Experiments	6
Table 4.2	Significant Waveheights and Periods	7
Table 4.3	Averaged Results of Seakeeping Experiments	8
Table 5.1	Results of Resistance Tests in Level Ice	11
Table 5.2	Results of Resistance Tests in Presawn Ice	12
Table 6.1	Ice Resistance Measurements and Predictions for Carter Hull Form	17
Table 6.2	Predicted Influence of Trim on Level Ice Resistance	17

1. INTRODUCTION

The following report documents the results of a model test program to ascertain the icebreaking efficiency, ice clearing ability, open water resistance, and sea-keeping performance of a hull form which was generated by a software developed by Carter [1], with the support of the Transportation Development Centre (TDC).

Preliminary studies have indicated that an improved icebreaking bow form may be achieved without degrading its open water performance.

In order to allow for realistic comparative assessment, a test program was devised where by the existing model of the Original R-Class was incorporated into the testing program to act as the benchmark against which the performance of the conceptual bow form could be compared. The selected Canadian Coast Guard R-Class icebreaker is known as particularly efficient, rivalling in performance with larger and more powerful ships.

The model tests were carried out in both the Ice Tank and the Towing Tank at the Institute for Marine Dynamics (IMD) in St. John's, during April 1990.

The test program is discussed, in some detail, in a report prepared by Lindstrom [2]*, and this document should be referred to for a detailed description of testing procedure and data analysis.

In this report, the models will be called respectively "Carter Hull Form" and "Original R-Class" in accordance with the designation adopted in Reference [2].

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* In the remaining part of this report, we shall refer to Lindstrom's report by the prefix "L". For example, Table L2 and Page L8 will mean respectively Table 2 and Page 8 of Lindstrom's report [2].

2. DESCRIPTION OF MODELS

The existing 1:20 scale model of the CCG R-Class icebreaker and the newly constructed 1:20 scale model of the Carter Hull Form, designated 327 and 439 respectively in accordance with IMD's numbering sequence, are both made of fiberglass complete up to the weatherdeck but with no superstructure. Both models have the standard IMD finish with ice-hull friction coefficients ranging from 0.035 to 0.049 and are fitted with twin propellers shafts with identical fairing cones and shaft bossings. The tow point was located at the center of gravity for both models during all tests.

Abbreviated lines plans are compared in Appendix A and hydrostatic particulars, as calculated using IMD's Blines hull definition software, are given in Table 2.1.

TABLE 2.1
HYDROSTATIC PARTICULARS

(See also Tables L1 thru L18 and Figures L1 thru L5)

GEOMETRICAL CHARACTERISTICS	R-Class	CARTER HULL FORM	
	DESIGN DRAFT	DESIGN DRAFT	DEEP DRAFT
Length on waterline (m)	4.691	4.508	4.885
*Length btwn perpend.(m), L	4.397	4.397	4.397
*Maximum beam (m), B	0.970	0.969	0.992
*Draught at midships (m), T	0.358	0.358	0.407
Displacement (m^3)	0.994	0.813	0.995
Wetted Surface Area (m^2)	5.476	5.104	5.794
L/B	4.533	4.535	4.433
L/T	12.286	12.286	10.817
B/T	2.710	2.709	2.440
Block coefficient, Cb	0.651	0.533	0.561
Midship coefficient, Cm	0.915	0.832	0.835
Prismatic coefficient, Cp	0.711	0.634	0.668
Waterplane coefficient, Cw	0.853	0.830	0.905
Roll Radius of Gyration (m)	0.651	0.533	0.561
Pitch Radius of Gyration (m)	0.915	0.832	0.835
Vertical Center of Gravity (m)	0.711	0.634	0.668
Metacentric Height from CG (m)	0.853	0.830	0.905

*Coefficients are based on starred parameters

3. TEST PROGRAM

The test program was designed to verify the possibility of improving the ice breaking efficiency of a bow without unduly affecting its open water performance. In order to compare both hulls accurately, a test program was devised whereby each hull was tested, under similar conditions, in open water and ice at design draft of 0.358 m.

Experiments in the towing tank were broken down into two parts: calm water resistance and seakeeping experiments. Experiments in the ice tank were also broken down into two parts: level ice resistance and presawn ice resistance. The original test matrix is given in Table 3.1.

Testing was conducted in the period 02 April to 02 May 1990. The first two weeks consisted of calm water resistance and seakeeping experiments in the towing tank, and the second two weeks consisted of ice tank testing in level and presawn ice.

During level ice resistance experiments, it was observed that, as ice thickness increases, the Carter Hull Form Model (439) would trim by the stern, causing the designed ice-belt region to be trimmed out of the water and thus rendered ineffective. It was decided to increase the draft of the model to 0.407 m and by doing so, making the displacement of the model equal to that of the Original R-Class. It was hoped that as the model trimmed by the stern the designed ice-belt region would come in contact with the ice surface.

Due to scheduling and contract restraints, only one additional ice sheet was added to the initial test program to re-test the Carter Hull Form at a "deep draft" equivalent to the displacement of the R-Class icebreaker. The additional test matrix is given in Table 3.2.

An extra test was also performed in the remainder of the thickest ice sheet (75 mm) with the model being trimmed by the bow in order to counterbalance the stern trim due to the vertical forces applied along the bow section while moving through ice. It was determined that the ice/hull interaction would then occur with the designed ice-belt.

TABLE 3.1
INITIAL TEST PROGRAM FOR BOTH MODELS
(Same level draft but different displacement)

- TOWING TANK
  - CALM WATER RESISTANCE
    - SHIP SPEEDS
      2 to 17 knots
  - SEAKEEPING EXPERIMENTS
    - SEASTATE #
      3, 5, 7
    - SHIP SPEEDS
      4, 9, 13 knots
- ICE TANK
  - LEVEL ICE RESISTANCE
    - ICE STRENGTH
      500 kPa
    - ICE THICKNESSES
      0.7; 1.0; 1.5 m
    - SHIP SPEEDS
      1.3;2.6;5.2;10.4 knots
  - PRESAWN ICE RESISTANCE
    - ICE STRENGTH
      500 kPa
    - ICE THICKNESSES
      0.7; 1.0; 1.5 m
    - SHIP SPEEDS
      1.3;2.6;5.2;10.4 knots

TABLE 3.2
ADDITIONAL TEST PROGRAM FOR CARTER HULL FORM MODEL
(Same displacement but different level draft)

- ICE TANK
  - LEVEL ICE RESISTANCE
    - ICE STRENGTH
      500 kPa
    - ICE THICKNESS
      1.0 m
    - SHIP SPEEDS
      1.3;2.6;5.2;10.4 knots
  - PRESAWN ICE RESISTANCE
    - ICE STRENGTH
      500 kPa
    - ICE THICKNESS
      1.0 m
    - SHIP SPEEDS
      1.3;2.6;5.2;10.4 knots

4. OPEN WATER TESTS

Experiments in the towing tank were performed at the design draft of 0.358 m using IMD's standard test procedures. Prior to testing, both models were fitted with trip wires to provide turbulence stimulation. The ballast weights were adjusted to give the required pitch and roll radii of gyration and transverse metacentric height.

4.1 Calm Water Resistance Experiments

A series of resistance tests were run in calm water over the speed range 2 to 17 knots. For each model, the specific total resistance coefficient was plotted versus Froude Number and a fair line fitted through the data. The faired results were then used to predict the ship resistance and effective power using the ITTC standard correlation allowance of 0.0004. Results are listed in Table 4.1 and shown graphically in Figure 4.1 for comparison purposes. It can be seen in this figure that:

- between 2 to 6 knots, the effective power of both hulls is virtually the same in terms of model test accuracy;
- above about 6 knots, the Carter Hull Form has a lower effective power than that of the Original R-Class.

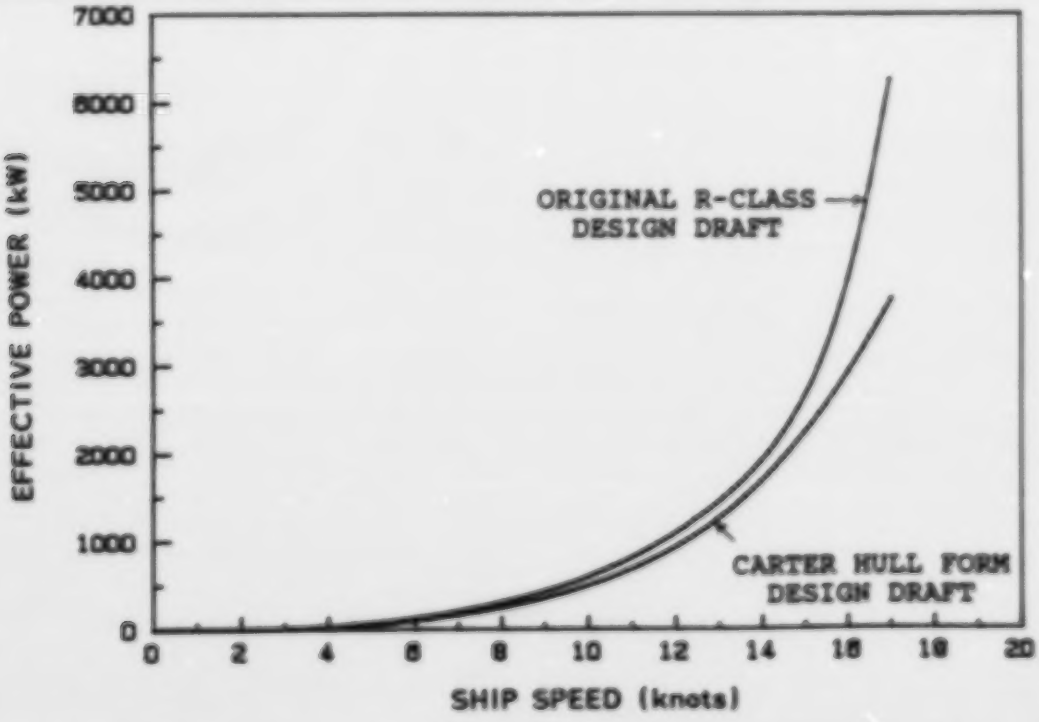
4.2 Seakeeping Experiments

During the seakeeping tests, both models were propelled by two outwardly turning four-bladed propellers, IMD's propellers 66L and 66R. The models were restrained by guiders, fore and aft, which were allowed to slide between rollers mounted on the tow tank carriage. This arrangement enabled the models to maintain a straight course down the centre of the tank while allowing the models to pitch and heave freely.

A wave probe mounted on the carriage provided the wave measurements while a six axis accelerometer array mounted at the centre of gravity of the models measured the motions of pitch and heave.

TABLE 4.1
RESULTS OF CALM WATER RESISTANCE EXPERIMENTS
(See also Tables L26 & L27 and Figure L13)

SHIP SPEED knots	ORIGINAL R-CLASS DESIGN DRAFT			CARTER HULL FORM DESIGN DRAFT		
	FROUDE NUMBER	RESIST. (kN)	POWER (kW)	POWER (kW)	RESIST. (kN)	FROUDE NUMBER
2.0	0.034	4	4	4	4	0.035
3.0	0.051	9	14	14	9	0.052
4.0	0.068	17	35	31	15	0.069
5.0	0.085	28	71	61	24	0.087
6.0	0.102	41	127	106	34	0.104
7.0	0.119	57	204	168	47	0.121
8.0	0.136	74	304	250	61	0.138
9.0	0.153	93	431	357	77	0.156
10.0	0.170	116	597	498	97	0.173
11.0	0.187	144	813	683	121	0.190
12.0	0.204	177	1090	929	150	0.208
13.0	0.220	216	1447	1254	188	0.225
14.0	0.237	266	1917	1684	234	0.242
15.0	0.254	343	2650	2237	290	0.260
16.0	0.271	484	3984	2921	355	0.277
17.0	0.288	714	6245	3741	428	0.294



PREDICTIONS OF EFFECTIVE POWER VERSUS SHIP SPEED
FIGURE 4.1

The seakeeping experiments were carried out on both models in long crested irregular waves with the models self-propelled and without any tow force.

The long crested irregular waves were generated by the standard ITTC two parameters spectrum. The experiments were conducted in three different seastates for a total run time corresponding to approximately 10 minutes full scale per seastate, and at speeds corresponding to approximately 4, 9, and 13 knots for both ships. Table 4.2 gives the significant waveheights and periods for the three seastates.

Table 4.3 presents the significant amplitudes at the different seastates and speed combinations calculated from the statistical analysis of the recorded time histories of each model's acceleration.

Testing of the Original R-Class model in seastate 7 had to be aborted due to swamping of the model caused by large motion amplitudes. The seastate 7 test on the Carter Hull Form was however completed.

The results of the seakeeping experiments in long crested irregular waves indicate that, within experimental error, there is little difference in motions between the two models with the Carter Hull Form being slightly better.

In a previous report [1], the analytical seakeeping assessment of both models was made utilizing the Standard Ship Motion Computer Program (SHIPMO4) developed by National Defence, Research and Development Branch. The theoretical results indicated that, in short-crested waves, the seakeeping responses in surge, sway, heave, pitch, and yaw would be very similar for both vessels. Furthermore, no significant difference in slamming pressure was predicted.

TABLE 4.2
SIGNIFICANT WAVEHEIGHTS AND PERIODS

SEASTATE	SIGNIFICANT WAVE HEIGHT (m)	MODAL WAVE PERIOD (sec.)	AVERAGE WAVE PERIOD (sec.)
3	1.0	4.80	3.70
5	3.0	7.80	6.00
7	5.0	12.30	9.50

TABLE 4.3
AVERAGED RESULTS OF SEAKEEPING EXPERIMENTS

(See also Tables L29 thru L34 and Figures L16 thru L27)

MODEL SPEED (m/s)	SEA STATE #	SIGNIFICANT AMPLITUDE (deg.)					
		ROLL		PITCH		YAW	
		R-CLASS	CARTER	R-CLASS	CARTER	R-CLASS	CARTER
0.5	3	0.03518	0.03594	0.06503	0.08173	0.00835	0.01999
	5	0.21512	0.15157	4.38777	3.86293	0.16511	0.20247
	7	0.57901	1.67576	7.60598	8.20930	0.25502	0.45180
1.0	3	0.05657	0.02248	0.04588	0.04121	0.00721	0.00685
	5	0.10493	0.12319	2.37490	2.22729	0.07726	0.13889
	7	***	1.36420	***	7.12788	***	0.55524
1.5	3	0.07075	0.03401	0.02775	0.08474	0.00775	0.00984
	5	0.19727	0.60642	1.91169	1.86146	0.04829	0.22431
	7	***	1.25398	***	6.37644	***	0.64398

MODEL SPEED (m/s)	SEA STATE #	SIGNIFICANT AMPLITUDE (m)					
		SURGE		SWAY		HEAVE	
		R-CLASS	CARTER	R-CLASS	CARTER	R-CLASS	CARTER
0.5	3	0.00123	0.00198	0.00013	0.00021	0.00151	0.00183
	5	0.10327	0.11203	0.00161	0.00147	0.04383	0.03324
	7	0.23810	0.29162	0.00661	0.07748	0.12427	0.11712
1.0	3	0.00074	0.00090	0.00016	0.00014	0.00079	0.00140
	5	0.05416	0.06239	0.00104	0.00153	0.03127	0.02886
	7	***	0.27864	***	0.06600	***	0.13262
1.5	3	0.00047	0.00087	0.00017	0.00024	0.00049	0.00115
	5	0.04087	0.04866	0.00094	0.00547	0.03589	0.03097
	7	***	0.20022	***	0.07278	***	0.14458

*** Test aborted due to swamping of the R-Class model.

5. ICE TESTS

For the ice tests, the models were towed through the ice on a rigid towing system consisting of a tow post and gimbal attached to a towing carriage. This towing system allowed the models to heave, pitch, and roll, while restraining surge, sway, and yaw.

IMD uses a doped ice as the modelling material. The percentage concentrations of EG/AD/S for the ice tests were 0.39/0.036/0.04. Once the ice sheet has nearly reached the target ice thickness, the ice sheet is tempered until the flexural strength of the model ice is within an acceptable range of its target value.

During the tempering period, flexural strength tests on the ice were performed to monitor the weakening process. Other ice properties measured during this time were elastic modulus and ice density. The ratio "elastic modulus/flexural strength", E/σ, varied from 958 to 2925 and the ice density was 0.937 ± 0.005.

Ice friction measurements were carried out on flat test plates which were painted at the same time and with the same finish as both models. The friction coefficients varied from 0.035 to 0.049 for both models. The hull-ice friction factor, measured at 0.04 on average, is much lower than the estimated value of 0.1 for a new icebreaker hull. Therefore, the results of ice resistance tests should be used for comparison purposes between the two hulls rather than absolute predictions of ship performance.

During both the level ice and presawn resistance tests, the towing carriage was programmed to run at four predetermined speeds of 0.15; 0.30; 0.60; and 1.2 m/s. Time history records for carriage speed and tow force were measured at a rate of 50 hz and averaged over the portion of the run where the steady state condition occured, usually the last full model length.

Immediately after each ice test, more cantilever beams were failed and the ice thickness measured at two metre intervals along both sides of the broken channel. The model average resistance, R, was then normalized to adjust the results to the target thickness and strength by multiplying the raw data points by:

$$R_{norm.} = R_{meas.} \times \frac{\text{Thickness targeted}}{\text{Thickness achieved}} \times \frac{\text{Strength targeted}}{\text{Strength achieved}}$$

A total of 29 tests were run to measure the level ice resistance and the clearing resistance of both models as a function of model speed and ice thickness. The actual test conditions and normalized results of resistance in level ice are listed in Table 5.1.

Following the resistance tests in each ice sheet, experiments were carried out to determine the components of icebreaking and ice clearing separately.

In these tests, a channel of width corresponding to the waterline beam of the model plus three times the ice thickness was hand sawed in the remaining of the ice sheet.

The ice within this channel was cut into a herring-bone pattern of average size similar to that which had been observed in the track left by the ship during the resistance tests through level ice.

The model was then towed through presawn ice at speeds as per those used in the level ice resistance. The results of the presawn experiments, normalized in the same manner as the level ice resistance, are listed in Table 5.2.

The clearing resistance of the R-Class and the Carter Hull Form in both the design and deep draft conditions is virtually the same.

Once the breaking and clearing resistance were broken down into components and the ice thickness and flexural strength were normalized at target values, the data points of total ice resistance were statistically analysed, using IMD's standard regression techniques. The results of these analyses are presented graphically in Figure 5.1, which combines Figures L6, L7, and L7.

From Figure 5.1, it can be seen that the Carter Hull Form in both the design and deep draft conditions has a lower ice resistance than that of the Original R-Class.

In the normal range of icebreaking speed, i.e. 3 to 6 knots (0.3 to 0.6 m/s model speed), for the same applied thrust as the Original R-Class, the speed of the Carter Hull Form would be increased respectively of about 40% and 84% in the light and deep draft conditions.

TABLE 5.1
RESULTS OF RESISTANCE TESTS IN LEVEL ICE

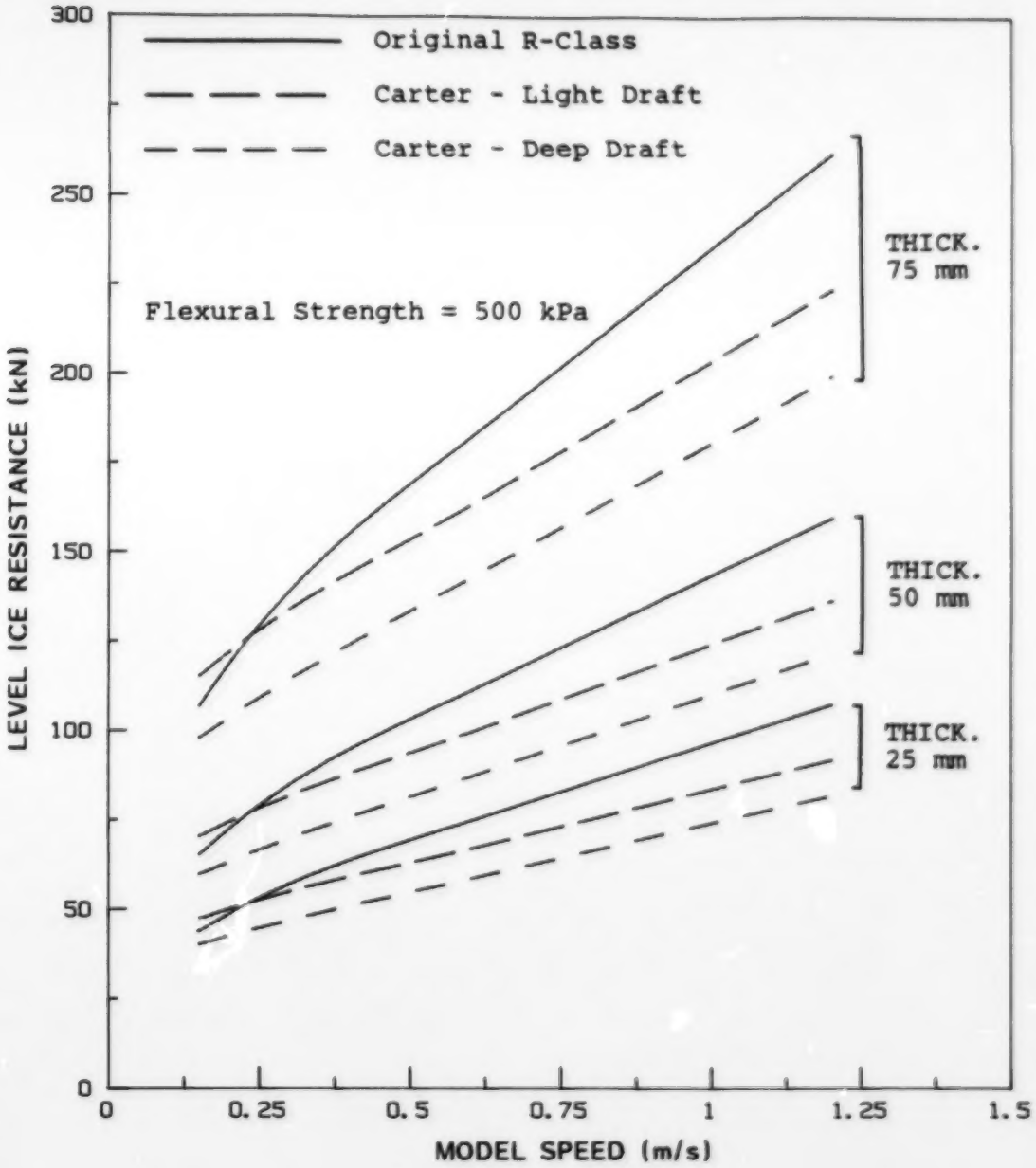
(See also Tables L20, L22, and L24)

ICE SHEET #	MODEL	ICE THICK. h(mm)	ICE STR. σ(kPa)	RATIO E/σ	MODEL SPEED V(m/s)	TOTAL RESISTANCE R(N)
1	R-CLASS DESIGN DRAFT LEVEL TRIM	34.5	26.0	1121	0.15	37.55
		33.6	26.0		0.30	42.10
		33.6	27.0		0.60	59.61
		32.3	32.0		1.20	111.58
2	R-CLASS DESIGN DRAFT LEVEL TRIM	51.3	25.0	2334	0.15	70.00
		50.6	28.0		0.30	84.93
		50.1	26.0		0.60	100.10
		48.7	26.0		1.20	156.46
3	R-CLASS DESIGN DRAFT LEVEL TRIM	77.5	29.0	2925	0.15	166.16
		77.4	28.0		0.30	237.28
		77.5	30.0		0.60	236.43
		77.5	24.0		1.20	327.01
4	CARTER HULL DESIGN DRAFT LEVEL TRIM	34.0	28.1	958	0.15	30.84
		34.0	23.1		0.30	33.56
		33.6	28.4		0.60	42.52
		32.8	25.7		1.20	70.15
5	CARTER HULL DESIGN DRAFT LEVEL TRIM	50.6	31.0	2580	0.15	83.58
		50.9	26.0		0.30	106.65
		49.9	31.0		0.60	95.44
		49.5	25.0		1.20	138.42
6	CARTER HULL DESIGN DRAFT LEVEL TRIM	76.9	30.0	2320	0.15	226.35
		77.8	29.0		0.30	238.08
		77.5	27.0		0.60	281.95
		77.4	28.0		1.20	384.43
6	CARTER HULL DESIGN DRAFT TRIM BY BOW	77.4	26.0	2320	0.30	176.57
7	CARTER HULL DEEP DRAFT LEVEL TRIM	50.8	26.0	2362	0.15	66.74
		50.2	25.0		0.20	70.69
		50.2	26.0		0.60	77.46
		50.1	22.0		1.20	127.41

TABLE 5.2
RESULTS OF RESISTANCE TESTS IN PRESAWN ICE

(See also Tables L21, L23, and L25)

ICE SHEET #	MODEL	ICE THICK. h(mm)	ICE STR. σ(kPa)	RATIO E/σ	MODEL SPEED V(m/s)	TOTAL RESISTANCE R(N)
1	R-CLASS DESIGN DRAFT LEVEL TRIM	33.0	22.4	1121	0.15	11.51
		33.3	22.4		0.30	14.26
		34.1	22.4		0.60	26.00
		32.3	22.4		1.20	57.97
2	R-CLASS DESIGN DRAFT LEVEL TRIM	51.7	20.1	2334	0.15	19.19
		50.5	20.1		0.30	25.53
		50.0	20.1		0.60	38.18
		47.1	20.1		1.20	82.48
3	R-CLASS DESIGN DRAFT LEVEL TRIM	77.8	18.4	2925	0.15	44.83
		76.5	18.4		0.30	48.21
		77.7	18.4		0.60	64.85
		74.9	18.4		1.20	109.08
4	CARTER HULL DESIGN DRAFT LEVEL TRIM	34.1	11.3	958	0.15	10.03
		33.0	11.3		0.30	13.45
		33.7	11.3		0.60	25.77
		32.0	11.3		1.20	50.99
5	CARTER HULL DESIGN DRAFT LEVEL TRIM	50.2	22.7	2580	0.15	15.74
		49.5	22.7		0.30	21.44
		50.7	22.7		0.60	36.37
		49.2	22.7		1.20	78.76
6	CARTER HULL DESIGN DRAFT LEVEL TRIM	76.6	19.8	2320	0.15	34.53
		77.6	19.8		0.30	39.50
		76.3	19.8		0.60	61.48
		75.9	19.8		1.20	114.08
6	CARTER HULL DESIGN DRAFT TRIM BY BOW	75.0	19.8	2320	0.15	39.94
7	CARTER HULL DEEP DRAFT LEVEL TRIM	51.2	15.8	2362	0.15	18.15
		51.2	15.8		0.20	22.78
		49.7	15.8		0.60	39.04
		51.1	15.8		1.20	78.12



REGRESSION EQUATION FOR LEVEL ICE RESISTANCE

FIGURE 5.1

6. ANALYSIS AND DISCUSSIONS OF RESULTS

6.1 Original R-Class

The 1:20 R-Class model, with a smooth low friction surface, was the icebreaker model selected, in 1978, by the Committee on Ships in Ice-Covered Waters of the International Towing Tank Conference (ITTC) for an international cooperative research program under which five ice testing facilities in various countries were to conduct a specified test program.

The range of parameters, V, h, and σ, prescribed by the ITTC Ice Committe, were within that of the present model test or nearly so. The results of the test program are presented and analysed in Reference [3]. The dimensional form of the regression equation for the ice resistance then obtained at IMD may be written:

$$R(N) = 0.0197h^2 + 2.12V^2h + 0.0147\sigma h$$

and the overall regression equation for the results from all facilities is:

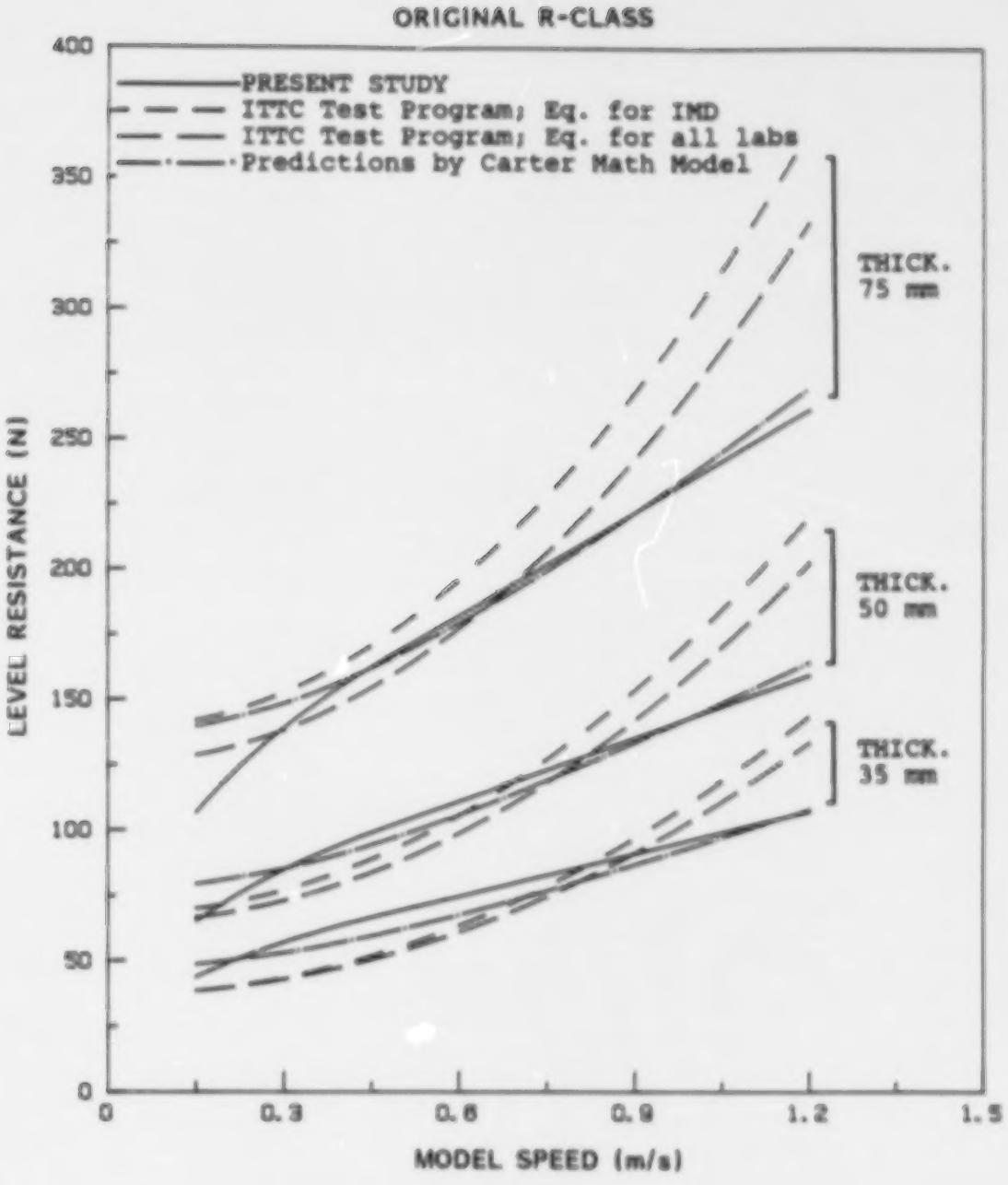
$$R(N) = 0.0153h^2 + 1.916V^2h + 0.0210\sigma h$$

in which, R, the level ice resistance is expressed in N; h, the ice thickness in mm; V, the model speed in m/s; and σ, the ice flexural strength in kPa.

The math model presented by Carter [4] was also run with the actual test conditions. Since the elastic modulus and the compressive strength were not measured at the time of each test series, rather than a contrived estimate, the default values supplied by the program were used for these two parameters. Input and output data are given in Appendix B .

From Figure 6.1, it can be seen that the various regression equations are comparable, and that variations are within the usual model test accuracy. Carter's predictions and the present model tests are in extremely good agreement.

However, it must be pointed out that the measured ice resistance shows a rapid drop at very low speeds, which is not generally observed. The propeller thrust to commence motion is higher than that required to maintain forward speed. To our knowledge, all resistance equations proposed in the literature, based either on model tests or on physical consideration, have the model speed raised to a power equal or greater than 1. This implies a resistance-speed curve either linear or more generally concave upward.



COMPARISON OF MEASURED ICE RESISTANCE WITH OTHER PREDICTORS AND PREDICTIONS BY CARTER'S MATH MODEL.

FIGURE 6.1

6.2 Carter Hull Form

As previously mentioned, during level ice testing of the Carter Hull Form, the model stern trim increased with ice thickness, thus causing the designed ice-belt region to be trimmed out of the water and thus rendered less and less effective.

In the design draft conditions, the trim of the model, as determined from the photographs taken during level ice experiments (See Appendix C), were respectively about 1.5°; 2.5°; and 4° for the 35, 50, and 75 mm ice sheets. Noting that ice/hull interaction within the designed ice-belt occurred only near the aft area of the bow, a test was run, in the remaining of the 75 mm ice sheet, with the model pre-trimmed 1.5° by bow. The resulting stern trim due to ice forces applied along the forebody was then, as estimated from photos, about 2.5° in the thickest ice sheet.

At this point, it was decided to increase the displacement of the model to that of the Original R-Class in order to decrease the trim, the new draft being 0.407 m. In these new deep draft conditions, the trim of the model was about 2° in 50 mm ice sheet and the ice/hull interaction within the designed ice-belt occurred only in the forward part of the bow, the aft part being submerged. (See Appendix C)

The math model was then run for the true geometrical parameters of the ice/hull contact area which were determined from the lines plan for each observed trim angle. Input and output data are given in Appendix C .

The measured and predicted level ice resistance are listed in Table 6.1 along with the actual test conditions. As shown in Figure 6.2, there is remarkable agreement between measurements and predictions.

The predicted values, given in Table 6.2, indicate a rapid increase of the level ice resistance as the model trims by the stern. A greater and greater part of the designed ice-belt is then trimmed out of the water.

Calculations also indicate that, for a complete ice/hull interaction within the designed ice-belt, the Carter Hull Form would show a 50% decrease in level ice resistance as compared to the Original R-Class. This extremely interesting point could be verified, easily and at low cost, by testing the model pre-trimmed 1.5° by bow in a 50 mm ice sheet. The stern trim due to ice forces would then cancel the initial trim by bow.

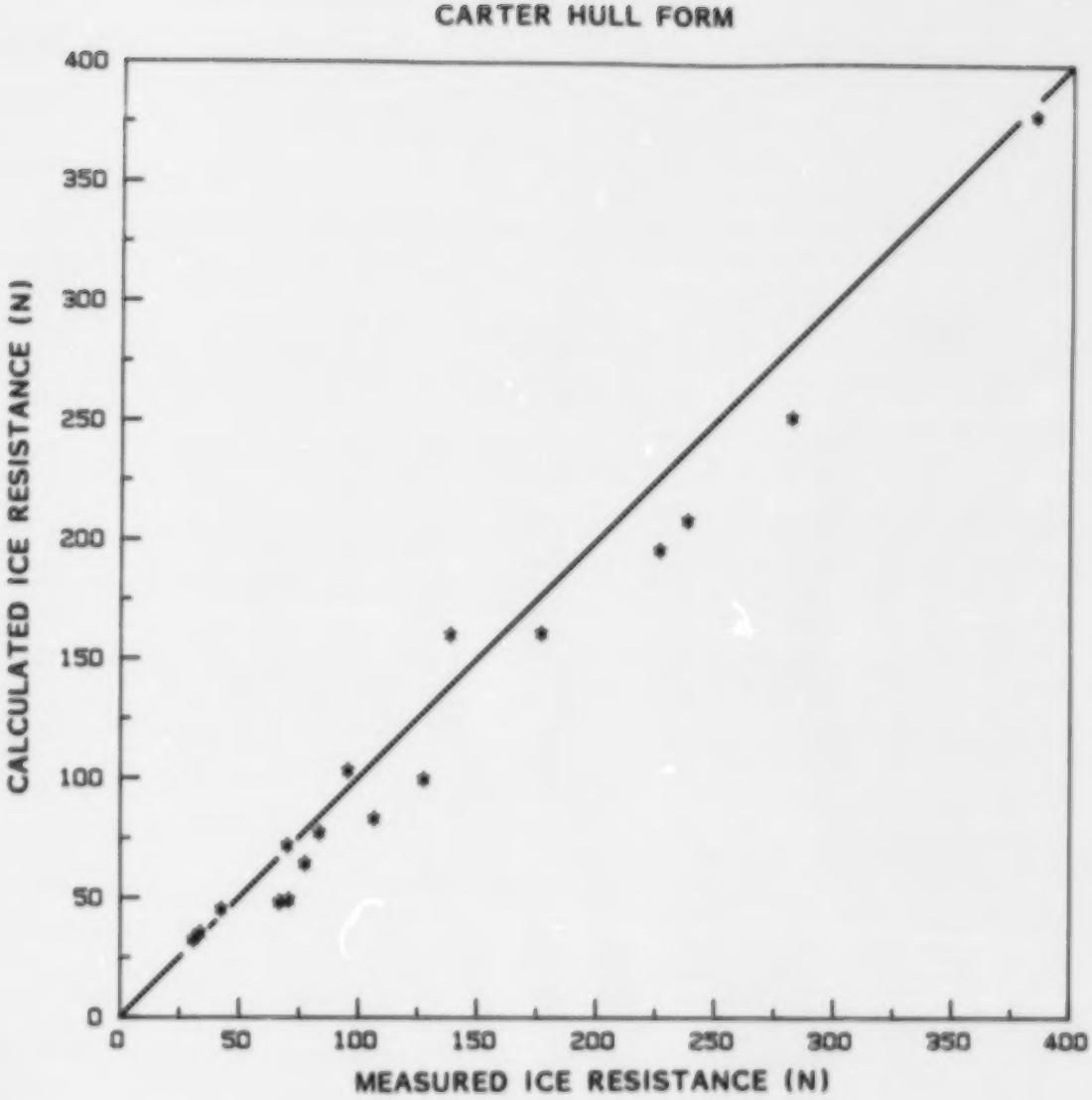
TABLE 6.1
ICE RESISTANCE MEASUREMENTS AND PREDICTIONS FOR CARTER HULL FORM

ICE SHEET #	ICE THICK. (mm)	STERN TRIM		MODEL DRAFT (m/s)	MODEL SPEED (m)	RESISTANCE measured (N)	RESISTANCE calculated (N)
		OPEN WATER (°)	LEVEL ICE (°)				
4	35	0	1.5	0.358	0.15	30.84	32.4
4	35	0	1.5	0.358	0.30	33.56	35.3
4	35	0	1.5	0.358	0.60	42.52	45.0
4	35	0	1.5	0.358	1.20	70.15	71.8
5	50	0	2.5	0.358	0.15	83.58	77.2
5	50	0	2.5	0.358	0.30	106.65	83.0
5	50	0	2.5	0.358	0.60	95.44	103.1
5	50	0	2.5	0.358	1.20	138.42	160.0
6	75	0	4	0.358	0.15	226.35	196.0
6	75	0	4	0.358	0.30	238.08	208.3
6	75	0	4	0.358	0.60	281.95	251.6
6	75	0	4	0.358	1.20	384.43	378.1
6	75	-1.5*	2.5	0.358	0.30	176.57	160.8
7	50	0	2	0.407	0.15	66.74	48.0
7	50	0	2	0.407	0.20	70.69	49.0
7	50	0	2	0.407	0.60	77.46	64.2
7	50	0	2	0.407	1.20	127.41	99.6

* Model trimmed by bow prior to testing

TABLE 6.2
PREDICTED INFLUENCE OF TRIM ON LEVEL ICE RESISTANCE CARTER HULL FORM

Trim Angle, φ (°)	Draft	$R_{trim=\varphi}/R_{trim=0}$		
		h=35 mm	h=50 mm	h=75 mm
0	Light	1.00	1.00	1.00
1,5	Light	1.32	1.37	1.42
2,5	Light	1.78	1.92	2.11
4	Light	2.27	2.47	2.73
2	Deep	1.18	1.20	1.21



COMPARISON BETWEEN ICE RESISTANCE MEASUREMENTS AND PREDICTIONS BY CARTER'S MATH MODEL

FIGURE 6.2

7. CONCLUSIONS

Test results,for both open water and ice, on the models of the Original R-Class and Carter Hull Form have been presented and analysed. Comparison of test results on the two hulls has indicated that:

1. In calm water, at ship speed between 2 to 6 knots, the effective power of both hulls is virtually the same; between 6 to 17 knots, the Carter Hull Form has a lower effective power. (page L6)

2. In long crested irregular waves, both designs have similar motions in all three considered seastates, with the Carter Hull Form being slightly better. Unfortunately, due to swamping of the Original R-Class Model, testing in seastate 7 had to be aborted. The seastate 7 test on the Carter Hull Form was completed. (page L6)

3. The Carter Hull Form, in both the design and deep draft conditions, has a lower ice resistance than that of the Original R-Class. (page L6) The drop in level ice resistance for the light and deep draft conditions is respectively 15% and 25% over the particularly efficient R-Class icebreaker.

4. The clearing ability of both hulls is virtually the same. (Tables L21, L23, and L25)

Generally the whole testing program can be considered to be a success. The test results clearly show that the computer program, proposed previously by the author [1], constitutes a useful tool to assist in maximizing the icebreaking efficiency without impairing open water resistance, seakeeping performance, and ice clearing ability.

Although the 15%-25% decrease in level ice resistance over the particularly efficient R-Class icebreaker is impressive, this is not considered to be optimum. Effectively, during level ice testing, the designed ice-belt region was partially trimmed out of the water and rendered more or less operative.

According to the predictions by the Carter's math model, which shows extremely good agreement with the measured ice resistance, the decrease would be much higher for a full ice/hull interaction within the designed ice-belt.

On the basis of the model test results, it is justified to make the following recommendations:

1. To run an additional test series in a 50 mm ice sheet with the Carter Hull Form Model being trimmed by bow prior to testing so as to obtain a complete ice/hull interaction within the designed ice-belt when the model is levelled by the ice forces acting along the bow section.

2. If the designed ice-belt proves to be as effective as predicted, to redesign the Carter Hull Form such that the ice/hull interaction always remains within the ice-belt region. This may be achieved by combining the three following measures:
   a) Widening the ice-belt region;
   b) Increasing the displacement so as to decrease the trim;
   c) Designing the ice-belt slightly trimmed by bow.

8. REFERENCES

[1] Carter,D. 1990 Parametric Study of Icebreaking Bow Forms Report TP 10193E Transportation Development Centre, Transport Canada, Montreal.

[2] Lindstrom,T. 1990 Comparison Experiments with 1:20 R-Class Model and Carter Hull Form for Icebreaking, Resistance and Seakeeping. Report TR-1990-11, Institute for Marine Dynamics, National Research Council, St. John's NF.

[3] Tatinclaux,J.C., Alekseyev,J., Enkvist,E., Kitagawa,H., Narita,S., Schwarz,J., Takekuma,K., and Williams,M. 1989 Comparative Model Tests in Ice of a Canadian Coast Guard R-Class Icebreaker, Soc. of Naval Architects and Marine Engineers, Transactions, Vol.97 pages 31-52, November 15-18, 1989, New York.

[4] Carter,D. 1987 Mathematical Model For Predicting Icebreaker Performance, Report TP8531E, Transportation Development Centre, Transport Canada, Montreal.

APPENDIX A

Abbreviated Lines Plans

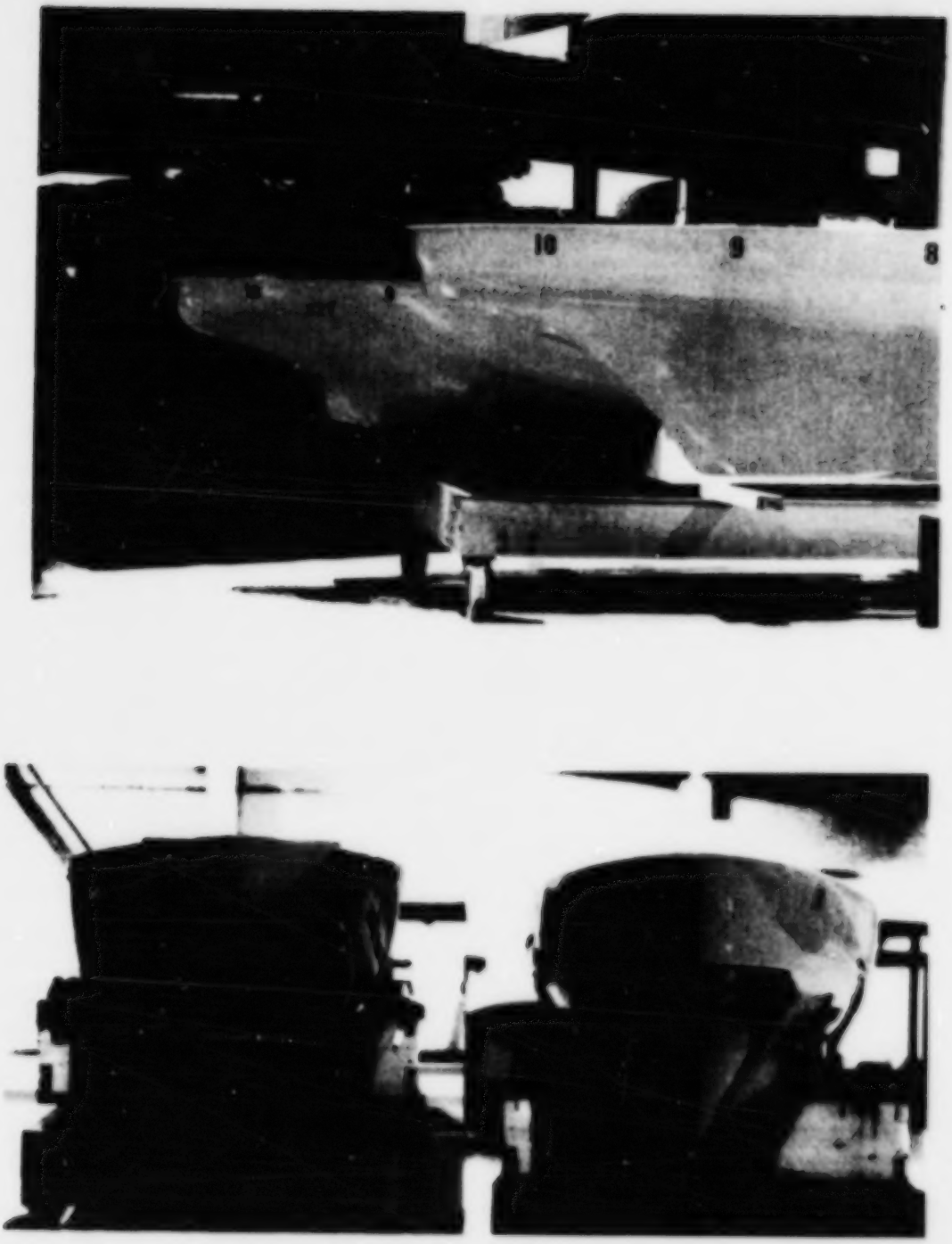
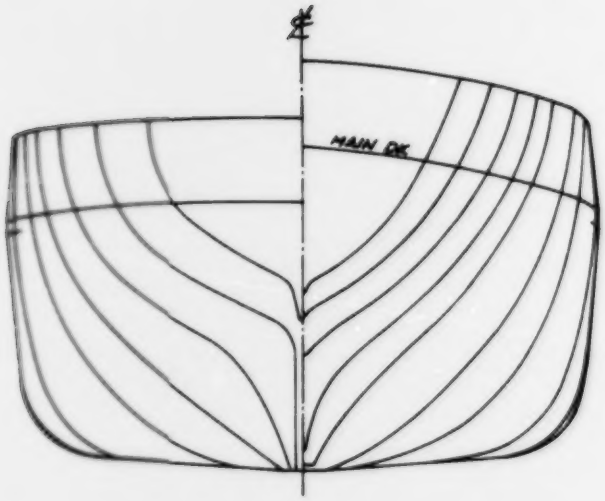
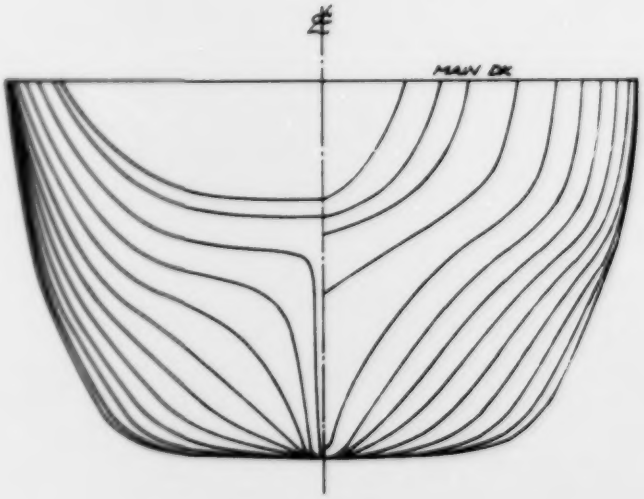


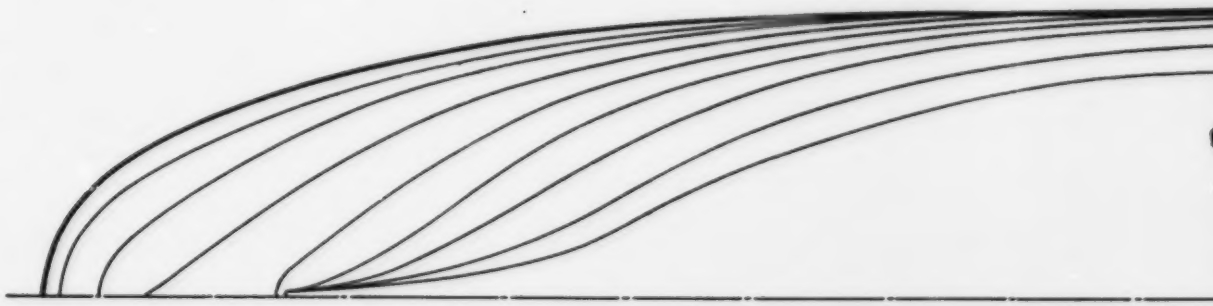
FIGURE A.1: VIEW OF THE TWO MODELS
CARTER HULL FORM (MODEL 439)
ORIGINAL R-CLASS (MODEL 327)



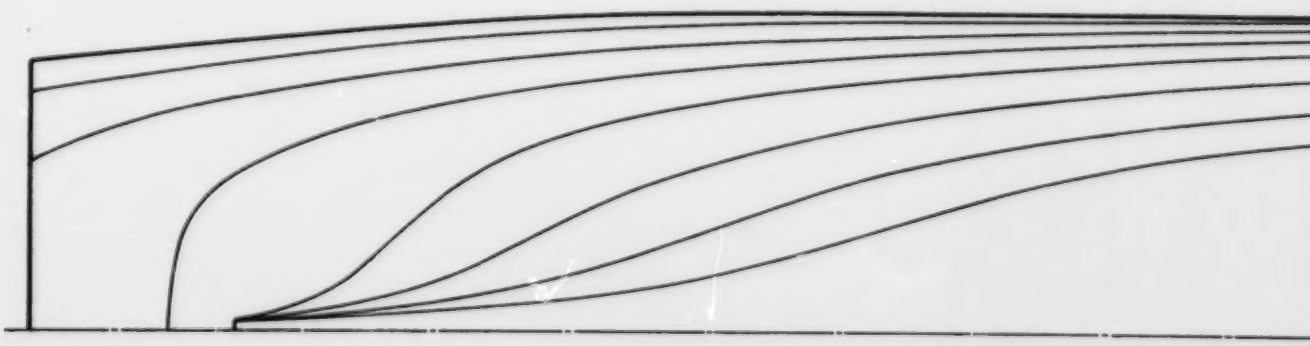
BODY PLAN OF THE 'R-CLASS'



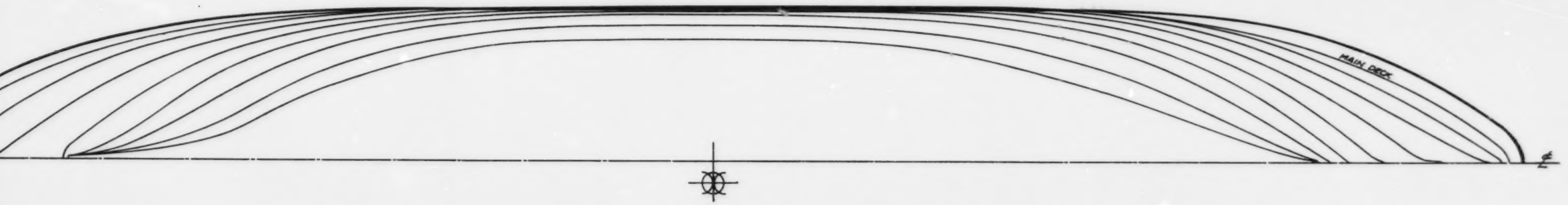
BODY PLAN OF THE CONCEPTUAL BOW FORM



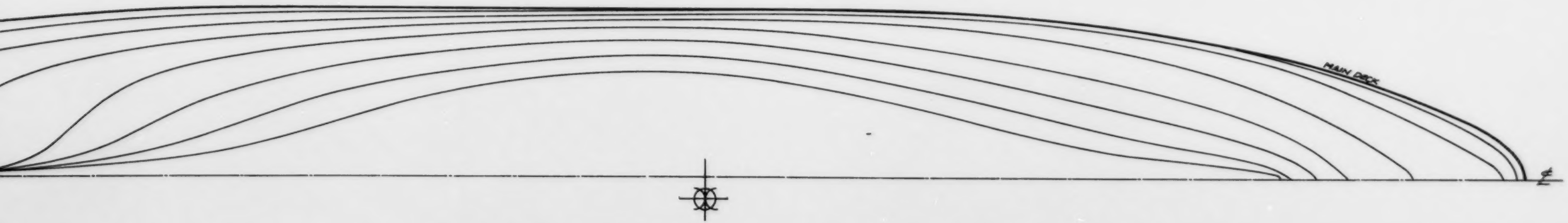
WA



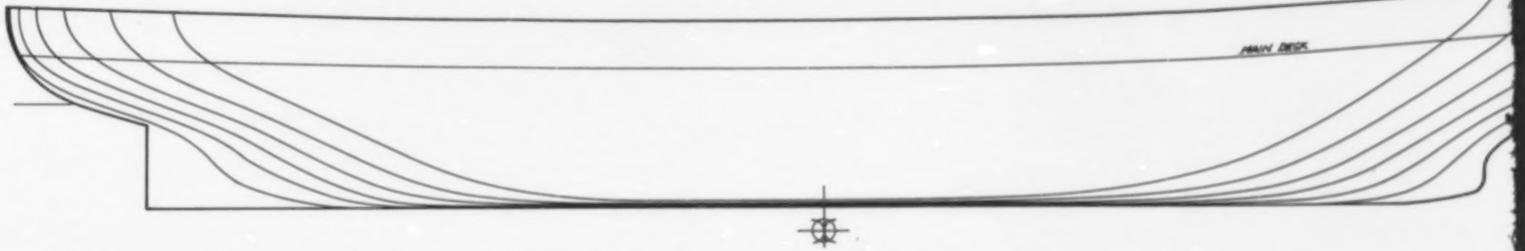
WATERLIN



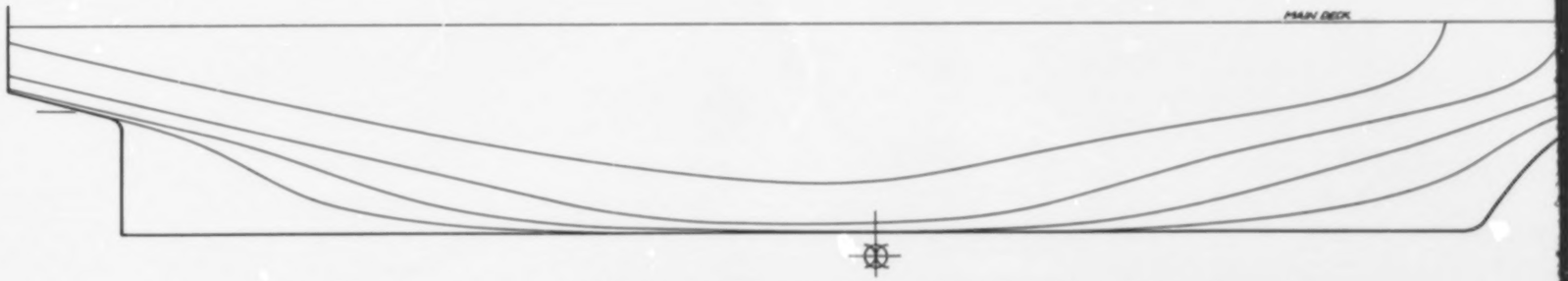
WATERLINES OF THE 'R-CLASS'



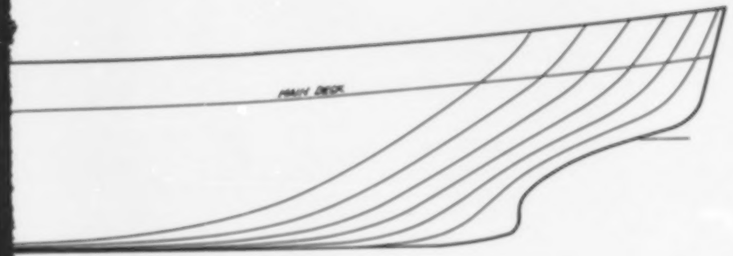
WATERLINES OF THE CONCEPTUAL BOW FORM



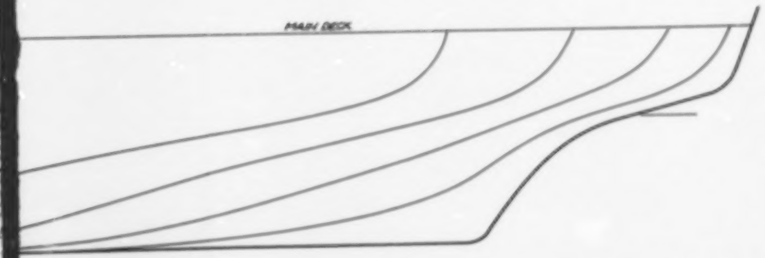
PROFILE & BUTTOCKS OF THE 'R-CLASS'



PROFILE & BUTTOCKS OF THE CONCEPTUAL BOW FORM



'R-CLASS'



TUAL BOW FORM

APPENDIX B

Original R-Class

Math Model Input and Output Data

LEVEL ICE RESISTANCE PREDICTIONS BY MATH MODEL

HULL DESCRIPTION...: 1:20 R-Class Model
WATERLINE.....: 0,358 m; Even Keel

X (m)	Y (m)	α (°)	β (°)	Γ (°)
0.00	0.49	0.0	5.3	44.0
0.47	0.48	3.5	8.5	40.0
0.93	0.42	11.3	16.0	36.2
1.16	0.36	18.9	24.7	33.8
1.40	0.26	24.8	35.2	31.8
1.51	0.20	26.8	41.1	29.8
1.63	0.14	28.8	46.9	27.3
1.74	0.08	30.9	53.6	24.6
1.86	0.00	32.5	60.0	16.0

X : distance forward of maximum beam;
Y : half breadth of waterline;
α : waterline spread angle;
β : section flare angle;
Γ : buttock angle.

CHARACTERISTICS OF ICE SHEETS

ICE SHEET #	THICKNESS (mm)	STRENGTH (kPa)	Ratio E/σ	FRICTION COEFFICIENT
1	35	25	Default	0,04
2	50	25	Default	0,04
3	75	25	Default	0,04

LEVEL ICE RESISTANCE PREDICTED BY MATH MODEL

MODEL SPEED (m/s)	LEVEL ICE RESISTANCE (N)		
	ICE SHEET #1 h=35 mm	ICE SHEET #2 h=50 mm	ICE SHEET #3 h=75 mm
0.15	48.8	79.4	139.7
0.30	53.2	85.4	148.5
0.45	59.7	94.5	162.1
0.60	67.9	106.1	179.4
0.90	87.0	133.6	221.4
1.20	108.2	164.6	269.5

APPENDIX C

Carter Hull Form

Math Model Input and Output Data

FIGURE C.1: CARTER HULL FORM MODEL, LIGHT DRAFT, IN 35 mm ICE SHEET, TRIM ANGLE ESTIMATED AT 1.5°

FIGURE C.2: CARTER HULL FORM MODEL, LIGHT DRAFT, IN 50 mm ICE SHEET, TRIM ANGLE ESTIMATED AT 2.5°

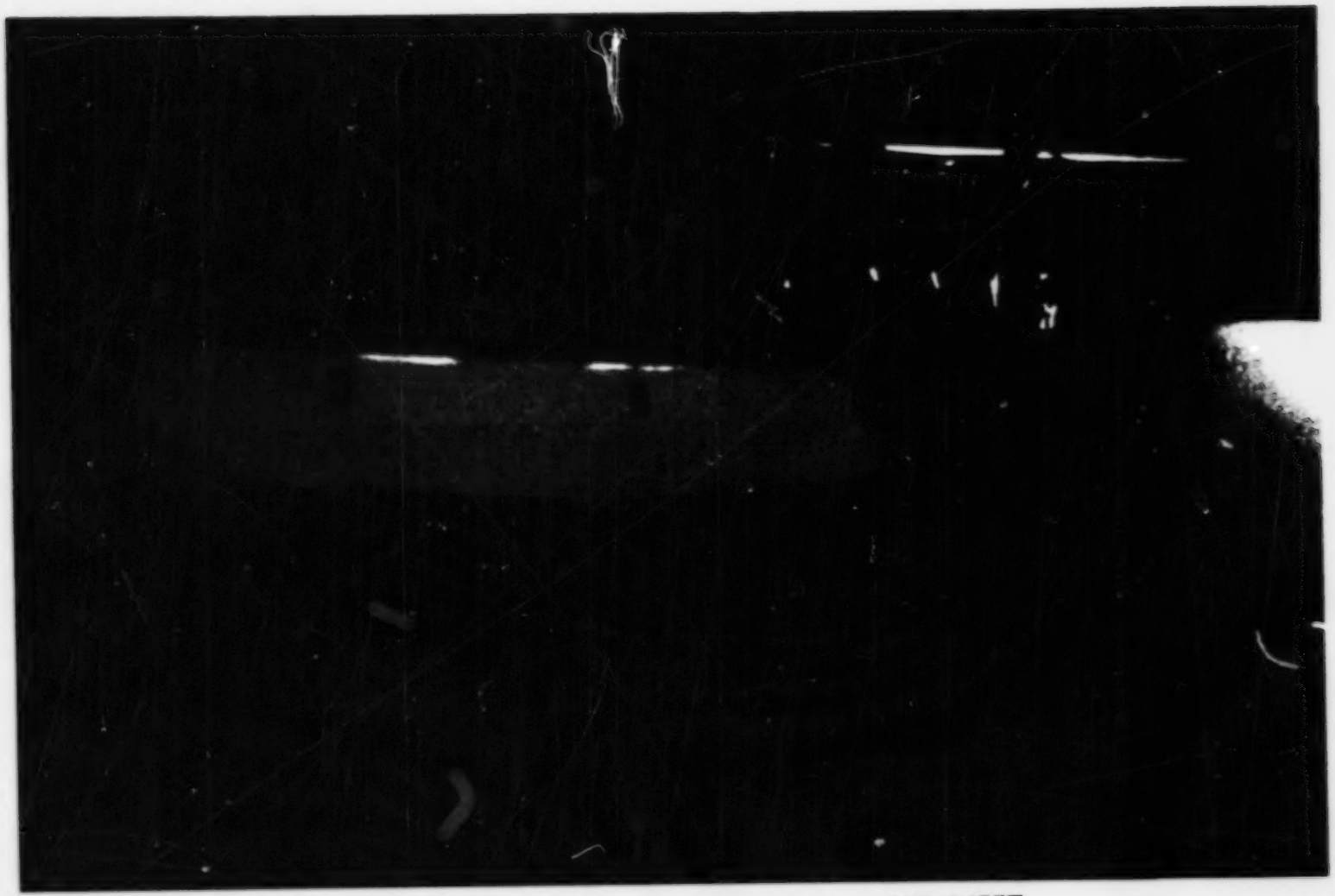


FIGURE C.3: CARTER HULL FORM MODEL, LIGHT DRAFT, IN 75 mm ICE SHEET, TRIM ANGLE ESTIMATED AT 4.0°

FIGURE C.4: CARTER HULL FORM MODEL, LIGHT DRAFT, IN 75 mm ICE SHEET, TRIM ANGLE ESTIMATED AT 2,5°, TRIMMED BY BOW -1,5° PRIOR TO TESTING

FIGURE C.5: CARTER HULL FORM MODEL, DEEP DRAFT, IN 50 mm ICE SHEET, TRIM ANGLE ESTIMATED AT 2,0°

LEVEL ICE RESISTANCE PREDICTIONS BY MATH MODEL

HULL DESCRIPTION...: CARTER HULL FORM
WATERLINE.....: 0,358 mm; Trim: 0 degrees in ice

X (m)	Y (m)	α (°)	β (°)	Γ (°)
0.00	0.49	0.0	12.0	0.0
0.44	0.48	2.0	20.0	3.0
0.66	0.46	4.0	28.0	5.0
0.88	0.45	7.0	35.0	7.0
1.10	0.42	9.0	40.0	9.0
1.32	0.38	12.0	47.0	10.0
1.54	0.33	15.0	50.0	12.0
1.76	0.26	22.0	53.0	23.0
1.98	0.15	28.0	58.0	20.0
2.20	0.00	45.0	72.0	18.0

X : distance forward of maximum beam;
Y : half breadth of waterline;
α : waterline spread angle;
β : section flare angle;
Γ : buttock angle.

CHARACTERISTICS OF ICE SHEETS

ICE SHEET #	THICKNESS (mm)	STRENGTH (kPa)	Ratio E/σ	FRICTION COEFFICIENT
4 5 6	35 50 75	25	Default	0,04

LEVEL ICE RESISTANCE PREDICTED BY MATH MODEL

MODEL SPEED (m/s)	LEVEL ICE RESISTANCE (N)		
	ICE SHEET #4 h=35 mm	ICE SHEET #5 h=50 mm	ICE SHEET #6 h=75 mm
0.15	24.4	40.1	71.7
0.30	26.5	43.1	76.2
0.45	29.8	47.7	83.2
0.60	33.9	53.6	92.1
0.90	43.4	67.5	113.7
1.20	54.0	83.1	138.4

LEVEL ICE RESISTANCE PREDICTIONS BY MATH MODEL

HULL DESCRIPTION...: CARTER HULL FORM
WATERLINE.....: 0,358 mm; Trim: 1.5° in ice

X (m)	Y (m)	α (°)	β (°)	Γ (°)
0.00	0.49	0.0	12.0	0.0
0.22	0.48	1.3	13.0	5.0
0.44	0.48	4.0	19.0	7.0
0.66	0.45	8.0	31.0	9.0
0.88	0.41	12.0	43.0	10.0
1.10	0.36	13.0	48.0	11.0
1.32	0.31	16.0	48.0	11.0
1.54	0.24	20.0	48.0	15.0
1.76	0.16	24.0	43.0	25.0
1.98	0.00	45.0	57.0	40.0

X : distance forward of maximum beam;
Y : half breadth of waterline;
α : waterline spread angle;
β : section flare angle;
Γ : buttock angle.

CHARACTERISTICS OF ICE SHEETS

ICE SHEET #	THICKNESS (mm)	STRENGTH (kPa)	Ratio E/σ	FRICTION COEFFICIENT
4	35	25	Default	0,04

LEVEL ICE RESISTANCE PREDICTED BY MATH MODEL

MODEL SPEED (m/s)	LEVEL ICE RESISTANCE (N)		
	ICE SHEET #4 h=35 mm	ICE SHEET #5 h=50 mm	ICE SHEET #6 h=75 mm
0.15	32.4*	54.9	101.9
0.30	35.3*	59.0	108.3
0.45	39.6	65.3	118.2
0.60	45.0*	73.3	130.8
0.90	57.7	92.3	161.5
1.20	71.8*	113.8	196.5

* Actual test conditions

LEVEL ICE RESISTANCE PREDICTIONS BY MATH MODEL

HULL DESCRIPTION...: CARTER HULL FORM
WATERLINE.....: 0,358 mm; Trim: 2.5° in ice

X (m)	Y (m)	α (°)	β (°)	Γ (°)
0.00	0.49	0.0	12.0	0.0
0.22	0.47	2.0	15.0	4.0
0.44	0.46	4.0	24.0	7.0
0.66	0.43	10.0	39.0	9.0
0.88	0.38	14.0	40.0	11.0
1.10	0.33	16.0	43.0	12.0
1.32	0.29	17.0	41.0	15.0
1.54	0.19	18.0	40.0	18.0
1.76	0.11	25.0	35.0	33.0
1.90	0.00	25.0	55.0	45.0

X : distance forward of maximum beam;
Y : half breadth of waterline;
α : waterline spread angle;
β : section flare angle;
Γ : buttock angle.

CHARACTERISTICS OF ICE SHEETS

ICE SHEET #	THICKNESS (mm)	STRENGTH (kPa)	Ratio E/σ	FRICTION COEFFICIENT
5 6	50 75	25	Default	0,04

LEVEL ICE RESISTANCE PREDICTED BY MATH MODEL

MODEL SPEED (m/s)	LEVEL ICE RESISTANCE (N)		
	ICE SHEET #4 h=35 mm	ICE SHEET #5 h=50 mm	ICE SHEET #6 h=75 mm
0.15	43.5	77.2*	151.3
0.30	47.4	83.0*	160.8*
0.45	53.3	91.9	175.5
0.60	60.5	103.1*	194.2
0.90	77.5	129.9	239.8
1.20	96.4	160.0*	291.8

* Actual test conditions

LEVEL ICE RESISTANCE PREDICTIONS BY MATH MODEL

HULL DESCRIPTION...: CARTER HULL FORM
WATERLINE.....: 0,358 mm; Trim: 4° in ice

X (m)	Y (m)	α (°)	β (°)	Γ (°)
0.00	0.49	0.0	12.0	0.0
0.22	0.46	7.0	15.0	4.0
0.44	0.43	8.0	34.0	8.0
0.66	0.40	13.0	37.0	10.0
0.88	0.34	16.0	38.0	13.0
1.10	0.28	17.0	38.0	14.0
1.32	0.20	18.0	38.0	16.0
1.54	0.13	20.0	36.0	24.0
1.76	0.04	23.0	29.0	42.0
1.83	0.00	24.0	15.0	52.0

X : distance forward of maximum beam;
Y : half breadth of waterline;
α : waterline spread angle;
β : section flare angle;
Γ : buttock angle.

CHARACTERISTICS OF ICE SHEETS

ICE SHEET #	THICKNESS (mm)	STRENGTH (kPa)	Ratio E/σ	FRICTION COEFFICIENT
6	75	25	Default	0,04

LEVEL ICE RESISTANCE PREDICTED BY MATH MODEL

MODEL SPEED (m/s)	LEVEL ICE RESISTANCE (N)		
	ICE SHEET #4 h=35 mm	ICE SHEET #5 h=50 mm	ICE SHEET #6 h=75 mm
0.15	55.5	99.2	196.0*
0.30	60.5	106.7	208.3*
0.45	67.9	118.1	227.3
0.60	77.2	132.5	251.6*
0.90	98.9	166.9	310.6
1.20	123.0	205.7	378.1*

* Actual test conditions

LEVEL ICE RESISTANCE PREDICTIONS BY MATH MODEL

HULL DESCRIPTION...: CARTER HULL FORM
WATERLINE.....: 0,407 mm; Trim: 2 degrees in ice

X (m)	Y (m)	α (°)	β (°)	Γ (°)
0.00	0.49	0.0	10.0	0.0
0.44	0.48	3.0	15.0	3.0
0.66	0.46	5.0	20.0	5.0
0.88	0.44	7.0	36.0	7.0
1.10	0.41	12.0	46.0	8.0
1.32	0.35	16.0	50.0	12.0
1.54	0.29	19.0	51.0	14.0
1.76	0.19	27.0	48.0	20.0
1.98	0.05	41.0	56.0	32.0
2.01	0.00	60.0	55.0	34.0

X : distance forward of maximum beam;
Y : half breadth of waterline;
α : waterline spread angle;
β : section flare angle;
Γ : buttock angle.

CHARACTERISTICS OF ICE SHEETS

ICE SHEET #	THICKNESS (mm)	STRENGTH (kPa)	Ratio E/σ	FRICTION COEFFICIENT
7	50	25	Default	0,04

LEVEL ICE RESISTANCE PREDICTED BY MATH MODEL

MODEL SPEED (m/s)	LEVEL ICE RESISTANCE (N)		
	ICE SHEET #4 h=35 mm	ICE SHEET #7 h=50 mm	ICE SHEET #6 h=75 mm
0.15	28.9	48.0*	86.9
0.20	29.6	49.0*	88.3
0.45	35.3	57.2	100.8
0.60	40.1	64.2*	111.5
0.90	51.4	80.8	137.7
1.20	64.0	99.6*	167.6

* Actual test conditions